THE STUDY ON THE DESIGN OF AN INTENSE-BEAM RFQ WITH STABILITY

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Abstract

Detailed studies and discussions on the determination of coupling gap and designing of the dipole mode stabilizer rods in an RFQ with intense beams have been done. By making use of the existent cold model of one section RFQ, measuring of the frequencies of the eigen modes, tuning and measuring of the RF field distributions and experiments related to the dipole mode stabilizer rods are carried out. By making comparison between the results from the experiments and from the computer simulations, the reliability and creditability of the code used in designing the RFQ cavity is proved. In the same time, a beneficial physical discussion on the design of RFQ with stability is given.

INTRODUCTION

The four-vane type RFQ used for our accelerator driven sub-critical nuclear power system (ADS) accelerates the proton beams with the initial energy of 75KeV and pulsed beam currents of 50mA (the average beam currents are 3mA) from the ion source to the final energy of 3.5MeV. The operating frequency of RFQ is 352.2MHz, and the length of RFQ is about 4.75m, which is about 5.57 times long as the RF wavelength. For such a long accelerating structure, small perturbations would distort the field distribution intolerably [1]. To overcome the disadvantage brought by the long length of RFQ, resonantly coupled structure is adopted [2,3]. As concerns our case, the RFQ consists of two resonantly coupled segments, and each segment consists of two sections connected by flange. The resonant coupling is implemented by separating the two segments by coupling plate. At the center of the coupling plate, an opened hole allows the vane tips of the neighbor segments to nearly touch. The capacitance between the vane tips of one segment and the other one provides the RF coupling between the two segments. The gap between the vane tips at the coupling joint is carefully chosen to make the frequency difference between the operating mode (TE_{210}) and its left and right side neighboring quadruple modes (TE_{211}) equally. To minimize the effect of the gap on the beam, its position is chosen to correspond to a zero crossing RF field when the bunch passes the gap. On the basis of perturbation theory [4], the accelerator structure stability is then best guaranteed.

However, the effect from the neighboring dipole modes (TE_{11n}) of the operating mode is also an important factor for the stability of RFQ. To avoid a possible detrimental effect brought by the nearby dipole modes, 4 dipole mode stabilizer rods [3] are mounted on the end plates and two sides of the coupling plate, respectively. In this paper, we show the determination of the coupling gap and the dipole mode stabilizer rods in our RFQ designing process.

THE COUPLING GAP

The cut-off frequency of RFQ cavity is chosen as 351MHz. The balance between the cut-off frequency and the operating one will compensate by the tuners. The inter-vane voltage is kept constant along the structure in our RFQ design. So, as concerns the operating mode (TE_{210}) mode, the coupling gap does not affect the operating mode frequency and its RF field distribution since no capacitance exists in the gap for this mode. But it is not the case for other modes, the frequency difference between the operating mode and the neighboring quadrupole modes at its left and right side can be chosen to be equal by adjusting the gap width. For our two-segments RFQ, the left and right side neighboring modes are π mode of TE_{210} ($^{\pi}TE_{210}$) and zero mode of TE_{211} ($^{0}TE_{211}$), respectively. Simulations show that, when the gap width $g = 1.8mm$, the frequency interval of $^{\pi}TE_{210}$, $^{0}TE_{210}$ and the interval of $^{0}TE_{210}$, $^{0}TE_{211}$ are nearly the same. Table 1 shows the simulation results.

Table 1: The frequency and Q value of the first five eigen modes in the case without rods

Quad. Modes	**Freq. (MHz)**	**Q**	**Dipole Modes**	**Freq. (MHz)**	**Q**
$^{\pi}TE_{210}$	349.01	8013	$^{\pi}TE_{110}$	343.39	8787
$^{0}TE_{210}$	352.11	9362	$^{0}TE_{110}$	344.49	9019
$^{0}TE_{211}$	355.25	7790	$^{0}TE_{111}$	350.94	7169
$^{\pi}TE_{211}$	357.78	7588	$^{\pi}TE_{111}$	353.46	7281
$^{\pi}TE_{212}$	371.30	5376	$^{\pi}TE_{112}$	367.43	5260

The frequency of $^{0}TE_{210}$ shown in the table is less than the objective operating mode frequency 352.2MHz because of the insufficient simulation accuracy, but its effect on the frequency difference between different eigen modes is omissible. As shown in table 1, the frequency interval of $^{\pi}TE_{210}$ and $^{0}TE_{210}$ is about 3.102MHz, and the interval of $^{0}TE_{210}$ and $^{0}TE_{211}$ is about 3.135MHz, which are almost equal. However, the neighboring dipole modes of the operating mode are very close to the operating mode, the frequency intervals between $^{0}TE_{210}$ and $^{0}TE_{111}$, $^{\pi}TE_{111}$ are only 1.176MHz, 1.343MHz, respectively. In addition, the Q value of the dipole modes is comparable to that of the operating mode. It is why the dipole mode stabilizer rods are used.

In figure 1, the normalized RF field distribution of $^{0}TE_{210}$ along the beam axis is given. Except the sharp down-drop at both entrance and exit of RFQ (the gaps at the ends of RFQ are about 1cm), the filed distribution flatness is about 1.2%. The flatness is defined as $(E_{\max} - E_{\min}) / E_{\max}$. Because of the comparable big simulation grid size, the sharp down-drop of field at the coupling gap is invisible.

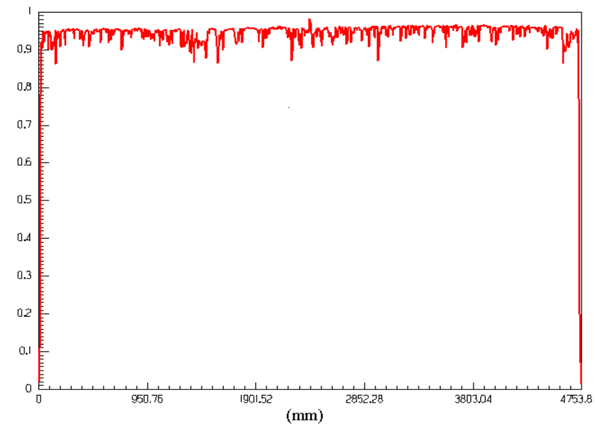

Figure 1: The normalized electric RF field distribution along the beam axis in the case without rods

DIPOLE MODE STABILIZER RODS

The dipole mode stabilizer rod is chosen as a copper plated stainless steel cylinder. The choice of the rod diameter should follow two conditions: first, the effect of rods on the operating mode is negligible; second, the requirement from water cooling and mechanical design is satisfied. To this ends, the diameter of rod is chosen as 15mm. By simulation, the exact position of the rods on the end plates and coupling plate could be fixed so that the rod effects on the operating mode frequency and RF field distribution are negligible. Based on the Slater's perturbation theory [4], the rod should locate at the position where the rod's perturbation magnitude to the operating mode electric field and magnetic field is the same. Obviously, the rod should be located on the line that passes through the central point of RFQ and forms an angle of 45^0 with the electrode central line. If one does not consider the disturbance to the field distribution from the undercuts at the ends and the coupling joint of RFQ, then SUPERFISH could be used to determine the rod position. Figure 2 shows the simulated one-eighth of RFQ by SUPERFISH. When the distance of rod from the center of

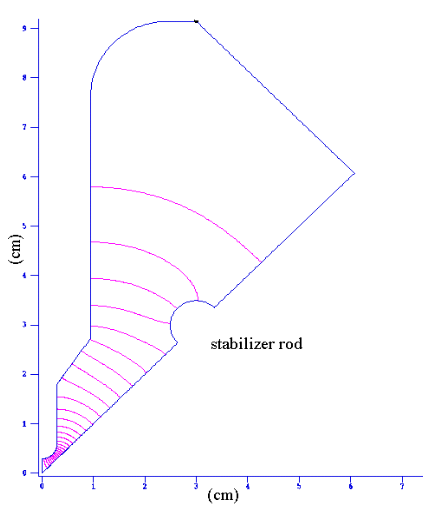

Figure 2: one-eighth RFQ simulated by SUPERFISH

RFQ $r = 42.3mm$, the cut-off frequency is 350.98MHz, which is only 0.02MHz different from that of the case without rod. If the effects of undercuts on the field distribution are taken into account, then 3-dimension code should be used. Certainly, the length of rod also has influence on the rod position. When the rod length $l = 15\,cm$, the result got by 3-dimension simulation is $r = 43.4mm$, which is very close to the result from SUPERFISH.

Table 2: The frequency and Q value of the first five eigen modes when the rod length $l = 15\,cm$.

Quad. Modes	**Freq. (MHz)**	**Q**	**Dipole Modes**	**Freq. (MHz)**	**Q**
$^{\pi}TE_{210}$	348.86	7768	$^{\pi}TE_{110}$	337.00	6582
$^{0}TE_{210}$	351.97	9163	$^{0}TE_{110}$	341.21	8281
$^{0}TE_{211}$	355.09	7569	$^{0}TE_{111}$	342.61	7055
$^{\pi}TE_{211}$	357.64	7351	$^{\pi}TE_{111}$	347.13	6919
$^{\pi}TE_{212}$	362.75	4698	$^{\pi}TE_{112}$	356.99	5263

Table 2 shows the variation of frequency and Q value of the eigen modes after the dipole mode stabilizer rods are mounted. As shown in the table, all the dipole modes have a drift towards the low frequency direction. Surely, the frequency drift magnitude is different for different modes because of the different field distributions. Now the dipole modes $^{\pi}TE_{111}$ and $^{\pi}TE_{112}$ become the neighbor of the operating mode, and the frequency interval of $^{\pi}TE_{111}$ and $^{0}TE_{210}$, $^{\pi}TE_{112}$ and $^{0}TE_{210}$ is 4.84Mhz and 5.02MHz, respectively. Comparing to the case without rods, now the frequency interval between the operating mode and its neighboring dipole modes becomes larger. Except the quadruple mode $^{\pi}TE_{212}$ (error arises from simulations), the frequency for the other modes basically keeps invariable. In figure 3, the normalized RF electric field distribution along the beam axis direction is shown. The field flatness is about 3.15%, which is little larger than that of the case without rods. However, the field step at the coupling joint takes a large portion of the field fluctuation. Based on the reference [5], the existence of field step at the coupling joint is due to the uneven frequency at the two sides of the coupling joint. Obviously, it is caused by the insufficient simulation accuracy.

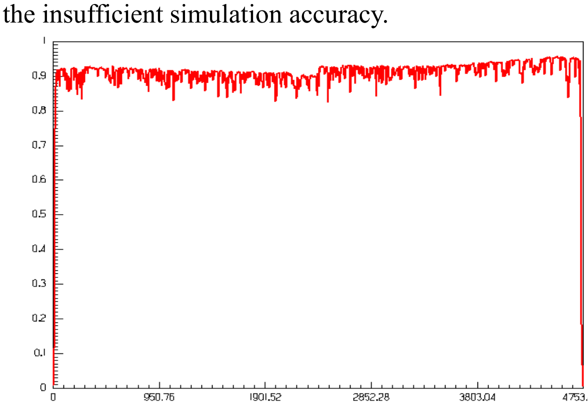

Figure 3: The normalized electric RF field distribution along the beam axis in the case with rods

COMPARISON BETWEEN SIMULATIONS AND EXPERIMENTS

In order to grasp the machining and welding technology, and to examine the creditability of the simulation code, one full-size section of RFQ cold model was fabricated. There are 16 tuners and 4 vacuum ports on the cavity, which is the same as the case of the real RFQ. But the electrode is not modulated. With the tuners, tuning and measuring of RFQ are carried out. The cavity is designed by using SUPERFISH and MAFIA, and the designed cut-off frequency is 351MHz. With all tuners flushed with the inside surface of the cavity, frequencies of the operating mode and the dipole modes (including the quadrants 1, 3 dipole mode D_{13} and the quadrants 2, 4 dipole mode D_{24}) are measured. Table 3 shows the measured results. For comparison, the simulated results are also listed in this table.

Table 3: The measured and simulated frequency of quadruple and dipole modes in the case without rods

Modes	**Meas. Freq. (MHz)**	**Simul. Freq. (MHz)**
TE_{210}	350.85	351.15
TE_{110} (D_{13})	344.82	347.81
TE_{110} (D_{24})	348.50	347.81

As shown in table 3, the difference between measured frequency and the simulated one for the operating mode is 0.3MHz, which is very near. But the value for the two measured dipole modes has a large difference, of which, the measured frequency of D_{24} is closer to the simulated one. The asymmetry of the four electrodes is cause by the deformation in the assembling and brazing process. The little difference between the measured results and the simulated ones demonstrates the creditability of the cavity design.

Experiments about the dipole mode stabilizer rods are also carried out. In view of the fact that each segment consists of two sections, and the rods are only installed on the end plates and coupling plate, we installed the rods only on one end plate of the cold model. Then, the experimental results and the simulation ones could be compared directly. Table 4 lists the measured and simulated frequencies of the quadruple and dipole modes when the rod length $l = 15\,cm$. For comparison, the case without rods is also listed in this table.

The measured results show that the effects of rods on the frequency of the operating modes are indeed small, the frequency variation for the operating mode is only 0.03MHz, which can be ignored. But the frequency change of the dipole modes is very large. The measured variation for the dipole modes D_{13} and D_{24} are 6.14MHz and 5.88MHz, respectively. The variation magnitude is also very close to the simulated result of 5.88MHz. Although the final rod length could be fixed by the experiment on the real RFQ, the simulated result about the rod length is also highly creditable.

Table 4: The measured and simulated frequency for the quadruple and dipole modes in the case with rods

Rod Length (cm)	0	15
Meas. Freq. of TE_{210} (MHz)	350.85	351.15
Simul. Freq. of TE_{210} (MHz)	351.15	351.15
Meas. Freq. of D_{13} (MHz)	344.82	338.68
Simul. Freq. of D_{13} (MHz)	347.81	341.93
Meas. Freq. of D_{24} (MHz)	348.50	342.49
Simul. Freq. of D_{24} (MHz)	347.81	341.93

DISCUSSIONS

For an RFQ consisting of resonantly coupled segments, the frequency interval between the operating modes and its neighboring quadruple modes is determined both by the segment length and the coupling width. When the length of the segment is definite, then the mode interval is decided only by the coupling gap width. So it is very critical in the choice of the gap width, and one must be careful in simulations. Because the coupling gap width has the order of 1.8mm while the RFQ length is 4.75m, the difference is more than three orders. In the meantime, the overall mesh size for the RFQ in 3-dimension simulations could not be very small due to limitation of computer memory and speed. In order to ensure the simulation accuracy, manual mesh could be used for the coupling gap. In addition, a criterion set by SUPERFISH simulation of RFQ is also conducive to raise the accuracy. Comparing to the determination of the gap width, since the length of the dipole mode stabilizer rods could be finally fixed by experiments, the simulation accuracy is not so important for the rod. Nevertheless, the experimental results show that the length of the dipole mode stabilizer rods determined by simulations is also highly reliable.

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